

NONLINEAR BRAIN DYNAMICS AND MANY-BODY FIELD DYNAMICS¹

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Abstract

We report measurements of the brain activity of subjects engaged in behavioral exchanges with their environments. We observe brain states which are characterized by coordinated oscillation of populations of neurons that are changing rapidly with the evolution of the meaningful relationship between the subject and its environment, established and maintained by active perception. Sequential spatial patterns of neural activity with high information content found in sensory cortices of trained animals between onsets of conditioned stimuli and conditioned responses resemble cinematographic frames. They are not readily amenable to description either with classical integrodifferential equations or with the matrix algebras of neural networks. Their modeling is provided by field theory from condensed matter physics.

Key words: neocortex, neurodynamics, nonlinear brain dynamics, phase transitions, quantum field theory

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The study of the brain functions in animal and human subjects requires observations and measurements of the brain activity and the formulation of dynamical models describing the observed behavior of neural populations, axons, dendrites, glia and cell bodies. We can describe brain functions at higher levels by using the tools provided by classical physics and statistical mechanics, with the associated mathematical machinery of algebraic methods and of sets of coupled differential equations. The achievements we have thus reached have enabled us to recognize and document the physical states of brains; the dynamics of neurons; the functions of membranes and organelles comprising their parts; and the molecular and ionic ingredients that constitute the basic neural machinery of brain function. We also observe, however, brain states which are characterized by coordinated oscillation of populations of neurons that are changing rapidly with the evolution of the meaningful relationship between the subject and its environment, established and maintained by active perception, which are not readily amenable to description either with classical integrodifferential equations or the matrix algebras of neural networks (Freeman, 2000; 2001; Vitiello, 2001). In this paper we report indeed our measurements of the brain activity of subjects engaged in behavioral exchanges with their environments whose modeling is provided by field theory from condensed matter physics rather than from classical dynamics.

Electroencephalographic (EEG) records were collected from 8x8 arrays of electrodes fixed on the pial surfaces of primary sensory cortices and entorhinal cortex of rabbits and cats trained to discriminate conditioned stimuli in the visual, auditory, somatic and olfactory modalities. The band pass filtered EEG signals under the Hilbert transform gave evidence for intermittent frames of spatial patterns of amplitude modulation of spatially coherent carrier oscillations in the beta (12-30 Hz) and gamma (20-80 Hz) ranges based on long-range correlation. The events resembled multiple overlapping frames in sequences during each act of perception, like cinematographic representations on multiple screens (Freeman, Burke, et al., 2003a; Freeman, 2004a). We identify these screens with regions in the embedding medium of the neurons, the neocortical neuropil. The large size, rapid formation, variety of detail, and perceptual remoteness from sensory input of normal frames requires a phase transition which we believe cannot be explained within the context of classical physics.

Observations of long-range correlations

The formation and maintenance of shared oscillations by phase transition (Freeman, 2004a,b; 2005) depends on rapid communication among the neurons at multiple hierarchical levels. The loop current of dendrites and axons is the chief agent for intracellular communication, and the action potential is the chief agent for intercellular communication from each part of the brain to every other part. This propagating wave is the mechanism by which multicellular organisms greater in size than about a millimeter overcome the limitations of diffusion as an essential technique for distant communication. However, the length of all but a few axons is a small fraction, only a tenth or less, (Houk, 2001) of the observed distance of long-range correlated activity, with the requirement for synaptic renewal at each successive relay. Even the presence of relatively sparse long axons, which provide for high velocity jumps to 'seed' areas over long distances cannot explain the long-distance spatial coherence with phase dispersion at every transmission frequency, especially for chaotic oscillations without fixed frequencies.

Further, although both electric fields and magnetic fields accompany dendritic currents, there are no significant electromagnetic fields (radio waves) to carry coordinating information over large intracortical and intercortical distances, because the electroencephalographic oscillations deriving from fields of dendritic synaptic current are too low in frequency and excessive in wavelength, and the electric and magnetic permeabilities differ in the ratio of 80:1. Intensities of the extracellular forces are 2-3 orders of magnitude smaller than the transmembrane potential differences. Resorting to electric potential gradients and Coulomb forces of the EEG has been shown (Freeman and Baird, 1989) to be inadequate to account for the long-range of the observed coherent activity, largely owing to the shunting action of glia that reduce the fraction of extracellular dendritic current penetrating adjacent neurons. Like the decay in diffusion potential the fall of electric potential with distance is too rapid, and the intensity of the Coulomb forces is too weak to explain either the abruptness of apparent discontinuities in the EEG phase with the onset of a phase transition or the entrainment of the oscillation on resynchronization within the observed time windows of 3-7 msec over distances of 1 to 19 cm (Freeman, Gaál, et al., 2003; Freeman, Burke, et al., 2003a; 2003b).

Our resort to many-body field theory

Thus, we are led to conclude that classical tools, such as, e.g., classical nonlinear dynamics and classical statistical mechanics, do not suffice. We then turn to the mathematical machinery of many-body field

theory that enables us to describe phase transitions in distributed nonlinear media having innumerable co-existing and overlapping ground states, actual and potential. Indeed, many-body field theory is the only existing theoretical tool capable to understand the dynamical origin of long range correlations, their rapid and efficient formation, their stability, the multiplicity of coexisting and non interfering ground states, their degree of coherence and ordering, the rich sequence of phase transitions, as we observed. It is a fact that many-body quantum field theory has been devised and constructed in the past decades exactly to face the understanding of features like ordered pattern formation and phase transitions in condensed matter physics, similar to the ones we observed in the brain dynamics, which could not be understood in the frame of classical physics.

This does not mean that the biochemistry, the usual neurophysiological analysis and/or any other classical tool of investigation must be put apart. Rather, it means that the brain studies made by using these traditional classical tools might be further boosted by the study of the underlying microscopic dynamics which allows to understand the richness of the observed phenomenology.

The field theoretic model to which we resort is the extension to dissipative dynamics (Vitiello, 1995; 2001) of the many-body brain model originally proposed by Ricciardi and Umezawa (1967) and developed by Stuart, Takahashi, et al. (1978; 1979) and by Jibu and Yasue (1992; 1995). According to such a model the production of activity with long-range correlation in the brain takes place through the mechanism of spontaneous breakdown of symmetry (SBS) (Umezawa, 1993). The immediate consequence of SBS in material substrates is the condensation of quanta, called the Nambu-Goldstone boson particles, or waves or modes, in the least energy state of the system (the system ground state or vacuum). The symmetry which is considered is the electrical dipole rotational symmetry (Del Giudice, Doglia, et al., 1985; 1986; Del Giudice, Preparata, et al., 1988; Jibu and Yasue, 1992; 1995). As we discuss in what follows, we believe we can follow this same path, since the water matrix and any of the biomolecules entering the brain cellular components are endowed with a characteristic electric dipole moment. The input coming to the brain from the environment is assumed to be the trigger of the breakdown of this symmetry. Dissipation plays a crucial role since the brain is permanently open to its environment. The dissipative dynamics is specifically responsible of the occurrence of a multiplicity of coexisting vacua, each one characterized by its own density of boson condensate (Vitiello, 1995).

Our bridge to nonlinear brain dynamics

The adoption of such a field theoretic approach enables us to model the whole cerebral hemisphere and its hierarchy of components down to the atomic level as a fully integrated macroscopic quantum system, namely as a macroscopic system which is a quantum system not in the trivial sense that it is made, like all existing matter, by quantum components such as atoms and molecules, but in the sense that some of its macroscopic properties cannot be described without recourse to quantum dynamics. One of the merits of the dissipative many-body model consists in the fact that the classicality of nonlinear, chaotic dynamics (Kozma, Freeman, 2002; Kozma, Puljic, et al., 2004; Skarda, Freeman, 1987; Tsuda, 2001) is derivable from it (Pessa and Vitiello, 2003; 2004;). As observed by Atmanspacher (2004), the dissipative quantum field model presents the further advantage of directly addressing to the neuronal level. There are other 'quantum models', mostly formulated in the Quantum Mechanics frame, which not only do not allow for long range correlations and phase transitions, but also do not provide the transition to the classical scale.

A central concern in our attempt to apply many-body physics is then expressed in the question: What might be the 'bridge' between microscopic, atomic and molecular, units and the macroscopic neural activity as we observe it? Typically, the unit of neural activity is taken to be the action potential, the dendritic postsynaptic potential, the chemical packet in the synaptic vesicle, or an electric operator in a gap junction or an ephapsis. On the one hand, the neuron, cell body, synapse, microtubule, vesicle, electrochemical waveform, and other microscopic structures and functions are not to be considered as quantum objects in our analysis. The Planck constant, h , is undeniably the unit of action at the atomic scale and below, but it is not the decisive factor at the level of neuronal populations. What appears to emerge from our experiments is a "wave packet" (Freeman, 1975/2004; 2000) acting as a bridge from quantum dynamics at the atomic level through the microscopic behavior of classical cells to the macroscopic properties of large populations of neurons. The wave packet we refer to is a mesoscopic collective field of action that has measurable field properties: the phase and the amplitude and their spatial and temporal rates of change (gradients) at each point in the sustaining neuropil. We stress that our wave packet is absolutely not to be confused with the notion of wave packet describing probability amplitudes in Quantum Mechanics (the

common denomination is only accidental). In our field-theoretic approach, the wave packet is a collective mode, in which a myriad of action potentials sustains a field of neural activity that we designated formerly as an "activity density function" (Freeman, 1975/2004), or as a "K-field" (Freeman, 2000). It gives rise to the observable fields of amplitude and phase functions, comprising action potentials recorded from arrays of microelectrode and dendritic potentials recorded from arrays of mesoelectrodes as the EEG. The wave packet or collective mode observed in our experiments turns out to be identifiable with the so-called Nambu-Goldstone boson wave or mode in Bose-Einstein condensates in the dissipative many-body model (Vitiello, 1995; 2001).

In this paper, for sake of shortness, we will only very briefly summarize the main points of our experimental observations and for the mathematical formalism of the dissipative brain model we refer to the original papers (Vitiello, 1995; Alfinito and Vitiello, 2000; Pessa and Vitiello, 2003; 2004) and to Vitiello (2001) for its extensive qualitative description. The present paper can be considered in some sense as an extended abstract of a more detailed description of the experimental results in relation with the dissipative many-body model which will be presented elsewhere (Freeman and Vitiello, 2005).

Five levels of neural field activity

In our experiments we have identified the following five levels of the activity that we describe by the dissipative many-body field theory model:

a) A basal state of symmetry. In a human subject in deep sleep we have observed the occasional appearance of a homogeneous field of fluctuations with no discernible spatial, temporal or spectral patterns. We characterize this state as one of "symmetry". This dynamical regime is characterized by parameters whose values do not belong to the windows of values that allow for the symmetry breakdown. Even in the presence of an external stimulus (provided it is below a threshold) the system "cannot" react to it (symmetry breakdown is not possible). The system "sleeps". External inputs at most create uninteresting perturbations. This is the transient "vacuum" state of the neocortex that is described by unbroken symmetry.

b) Sustained deep sleep. These transient epochs in deep slow wave sleep are embedded in fields of spatial patterns of phase. The fluctuations appear to result from continuous bombardment of all areas of neocortex by other parts of the brain, including inputs from the sensory receptors relayed mainly through the thalamus and mainly irrelevant, because it is the work of cortex by habituation to establish filters to mitigate the impact of such unavoidable bombardment on cortices. The continual perturbation gives rise to myriad local phase transitions characterized by the conic phase gradients, which are quenched as rapidly as they are formed, thereby maintaining the entire cortex in a robust metastable state. The critical parameter is the mean firing rate of neurons that is homeostatically maintained by mutual excitation everywhere by thresholds and refractory periods. The phase cones have no indistinguishable amplitude patterns, so we infer that they are related to SBS with a vanishingly short-lived order parameter.

c) The awake rest state disengaged from the environment. The ranges of parameter allowing higher-order SBS become potentially accessible under the influence of external weak but behaviorally significant stimuli. The temporal phase differences appear as patterns of coordinated analytical phase differences (CAPD), in which each plateau of minimal phase differences is accompanied by a peak in mean amplitude, but without discernible or reproducible spatial amplitude modulated patterns, owing to the lack of engagement.

d) The engaged state with arousal. The rest state evolves into an aroused state with increased amplitude of oscillations in the background dendritic current that accompanies incipient engagement of the brain with the external world including the body. There is an implicit differentiation of the set of compatible states, which is only realized by the overt emergence of an amplitude pattern (Freeman, Viana Di Prisco, 1986) that is classifiable, and that arises from SBS triggered by a relevant stimulus. We find evidence for intermittent frames of spatial patterns of amplitude modulation of spatially coherent carrier oscillations in the beta and gamma ranges based on long-range correlation resembling cinematographic frames of stationary images. The observed recurrence of patterns points to a sequence of phase transitions. The relevant role of the dissipative dynamics of the many-body model manifests here in the possibility for the simultaneous overlapping of a multitude of ground states labelled by different values of the order parameter without, or with reduced, reciprocal interferences and preserving their distinct autonomy. Evidence for this is found in the observed recurrence of patterns suggesting that they overlap, largely owing to the autonomy of the neurons in the cortical populations (Freeman, 2005). This enables them to participate in multiple coordinated or coherent domains simultaneously, by contributing the covariance of only a small percentage

of the total variance of their activity to the order parameter to which they contribute and in accordance to which they adapt their behaviours.

The description of the formation of coherent domains is a distinctive feature of the many-body model (Del Giudice et al., 1988; Alfinito et al., 2002). The observation of the multitude of ground states and of coherent domains provides a strong justification for exploring the description of nonlinear brain dynamics in terms of the dissipative many-body model. The concept of the boson carrier and the boson condensate enables an orderly and inclusive description of the phase transition that includes all levels of the macroscopic, mesoscopic, and microscopic organization of the cerebral patterns that mediate the integration of the animal with its environment, down to and including the electric dipoles of all the myriad proteins, amino acid transmitters, ions, and water molecules that comprise the quantum system. This hierarchical system extending from atoms to whole brain and outwardly into engagement of the subject with the environment is the essential basis for the ontogenetic emergence and maintenance of meaning through successful interaction and its knowledge base within the brain. We stress once more that neuronal cells and other macroscopic structures are by no means considered quantum objects in our analysis. No ambiguity should be born on this point. The SBS provides the bridge, or change of scale, from the microscopic quantum dynamics to the macroscopic behavior of classical cells and their constructs. The sequence of states is reversed on the return from engagement to rest, then to sleep and the transients with maximal disorder.

e) The seizure state. A departure from this sequence has been observed (Freeman, Holmes, 2005; Freeman, Holmes et al., 2005) in the period preceding onset of a complex partial seizure consisting of spikes at 3/s accompanied by "absence" (loss of consciousness) and stereotypic motor automatisms. This observation attests to the importance of long-range correlation for the maintenance of normal metastability of the cerebral cortex. The seizure has been simulated (Freeman, 1986) under the conditions of a deficit of excitation and an excess of activity of inhibitory neurons constituting regenerative, positive feedback.

Description of multiple ground states with the many-body model

Our measurements of the spatial patterns of dendritic currents in the primary receiving areas have repeatedly demonstrated dependence of the patterns on the history, context, and significance of sensory inputs, in a word on the meanings of inputs (Freeman, 2003a; 2003b; Freeman, Rogers, 2003) and not on their features. We are now able to conceive a hierarchy of brain states of varying levels of symmetry and order, with the mechanisms of spontaneous symmetry breaking by which phase transitions occurs. We see an act of perception as having three stages: the attentive stage of hypothesis formation in an array of ground states that we have previously described as an attractor landscape with multiple basins (Freeman, 2005); the testing stage of selection by input of one of the basins among these ground states leading to the emergence of gamma wave packets in the neuropil of multiple primary sensory areas that express the attractor; and the assimilation stage with emergence of adaptive beta wave packets in the hemispheres of the forebrain by synaptic modification with learning that modifies the attractor and its basin.

The essence of perception is the exceedingly rapid assimilation of the self to the changing conditions in the environment while maintaining a historic identity across change. These operations require that massive numbers of neurons cooperate in spatial and temporal patterns that shift rapidly in concert with the surround. By repeated trial-and-error each brain constructs within itself an understanding of its surround, which constitutes its own world that we describe as its "double" (Vitiello, 2001). It is an "active" mirror, because the environment impacts onto the self independently as well as reactively. The relations that the self and its surround construct by their interactions constitute the meanings of the flows of information that are exchanged during the interactions. A major difficulty in seeking to verify this theory of perception experimentally is to model the dynamics of very large numbers of neurons without submerging their unique identities in statistics. Only in the past two decades has the technology become widely available for recording and measuring large-scale images of brain activity with sufficient detail to reveal the intrinsic structures of the activity relating to behavior. The frontier now resides in the theory. On the one hand, the microscopic orientation of neural networks can express the dynamics of neurons even to the level of individual synapses, but they do not scale up to the millions and even billions of neurons that cooperate in perception. On the other hand, the macroscopic approach of brain imaging using hemodynamic techniques (fMRI, PET, SPECT), statistical mechanics, differential equations, and the concepts of representation from artificial intelligence fail to encompass the incredible variety of neuronal detail that is required to match brain functions. Now it turns out that the conflicting demands of massive numbers and intricate detail are not unique to brain science, but have been met in a broad range of fields in science over the past half

century. It is expedient, therefore, for brain scientists and theoretical physicists to pool their resources and find common cause, as we have done in describing the correspondences between brain dynamics and quantum field theory.

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